SPHINX

Structure Probing by Holographic Imaging at Nanometer scale with X-ray lasers

Channeling 2020

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June 9th 2023 Riccione

Qualitative comparison of X-ray imaging techniques

X-ray imaging

-low contrast for samples with similar compositeness (biological cells, multilayer nano lithography, etc.)

-bi-dimensional reconstruction using the amplitude information

- 2D phase contrast imaging (with reduced magnification)

- 3D info from long, multiple exposures(tomography) with ~10^2 nm resolution and no timing information or from diffractive patterns, often requiring polymer embedding, staining of freezing (in vitro) or averaging multiple similar samples

-large samples and organisms can be investigated

XRF imaging

-bi-dimensional, micrometer resolution
-provides elemental compositeness info

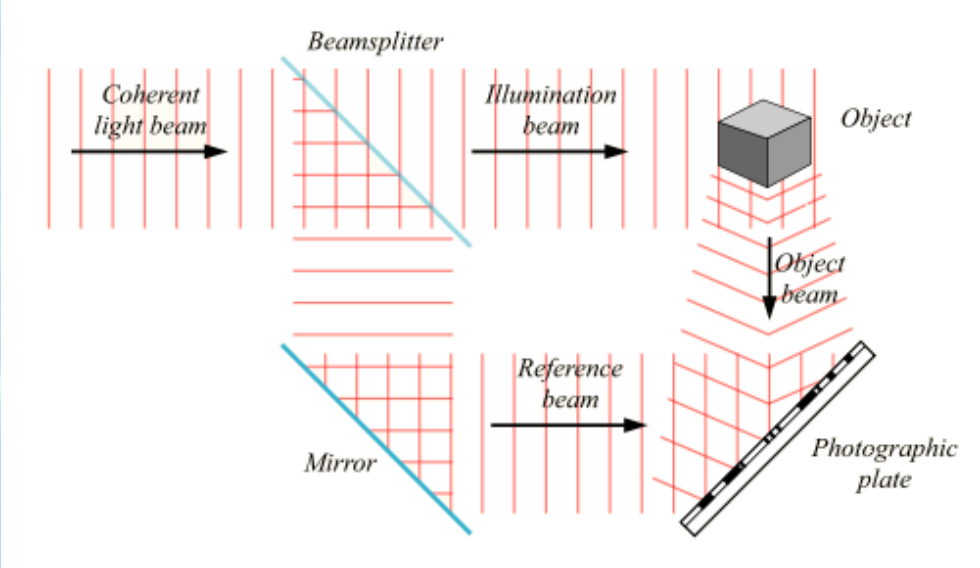
X-ray holography (absorption or phase contrast) -direct tri-dimensional reconstruction
-on **FEL**s, allows femtosecond time resolution, thus providing real-time info on the structure, possibility to monitor molecular processes
-small samples (biologic cells, microstructures, nanobots)

XRF holography

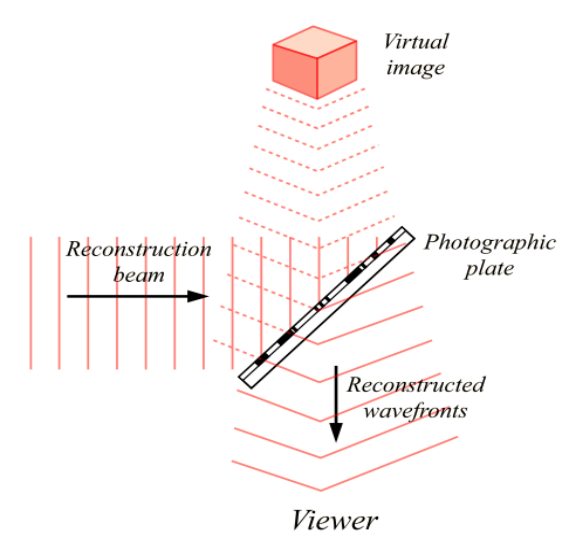
-atomic resolution (~Å), works on regular patterns

Basic holography method

Exposure



Reconstruction



$$|E_O + E_R|^2 = E_0 E_R^* + |E_R|^2 + |E_O|^2 + E_O^* E_R$$

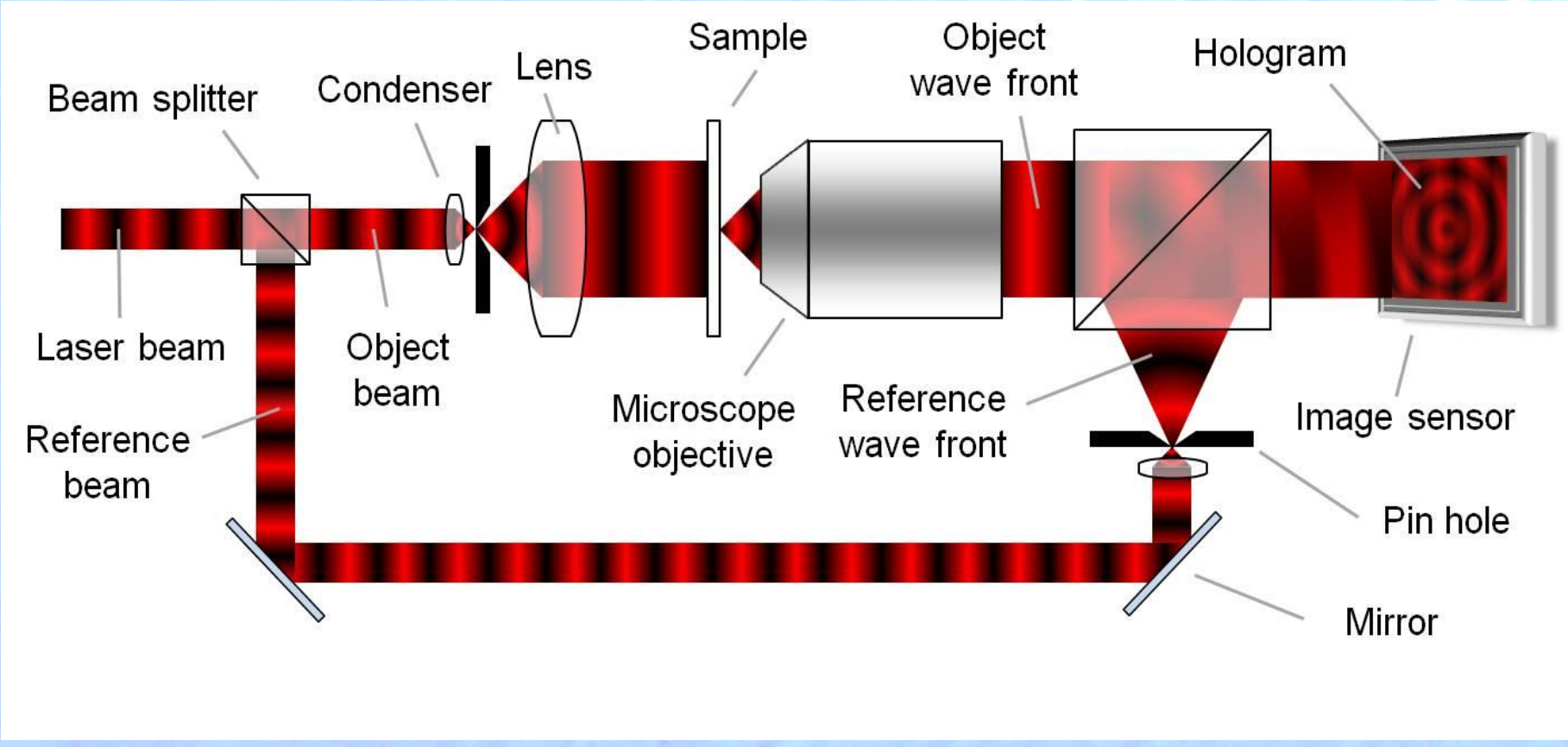
E_O - *object field,* E_R - *reference field*

$$E_R(x,y)h(x,y) = \left[h_0 + \beta\tau\left(a_R^{\,2} + a_o^{\,2}\right)\right]E_R(x,y) + \beta\tau a_R^{\,2} E_O(x,y) + \beta\tau E_R^{\,2}(x,y)E_o^{\,*}(x,y)$$

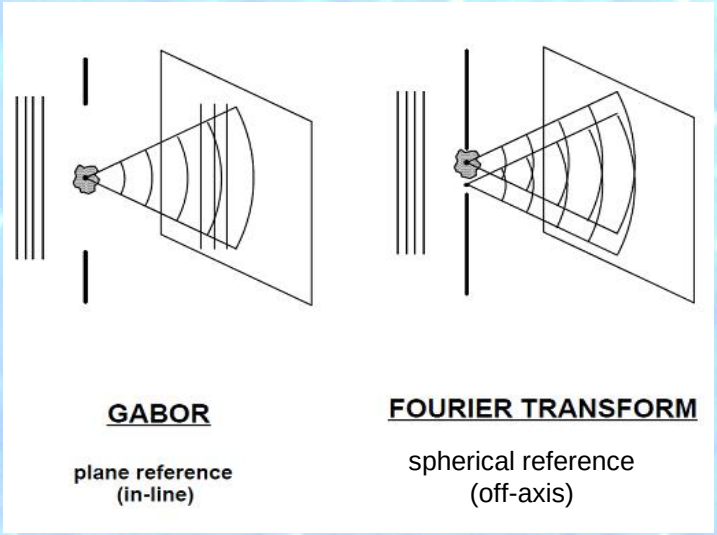
h(xy) - hologram function, β *- slope amplitude transmittance vs. exposure*

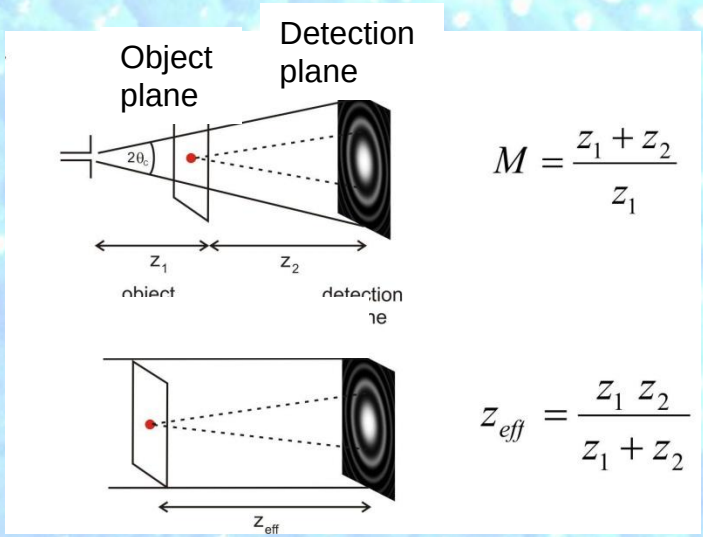
Digital holography

In the case of digital holograms, the photographic plate is substituted by CCD sensors, while reconstruction is performed by computing the interference. In particular, in digital holographic microscopy, beam condensers/expanders are required, for matching the beam-sample-sensor sizes.



Basic setup configurations for X-ray digital holography





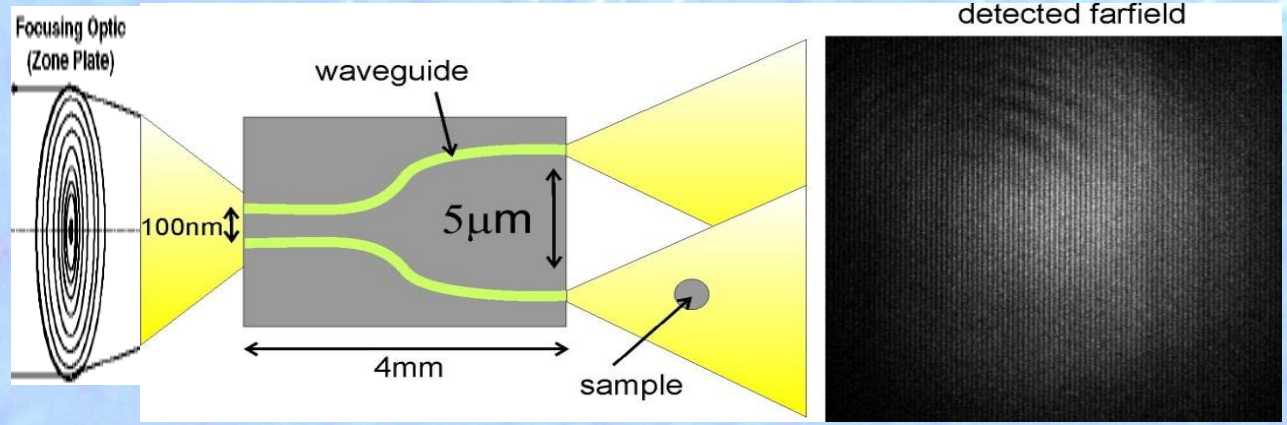
Optimizing Z for best sampling frequency:

Z=1.22*N*δr*Ps/λ

Z exposure distance
δr minimal probe element
N number of pixels
Ps pixel size
λ wavelength

low flux trough the sample (image beam)

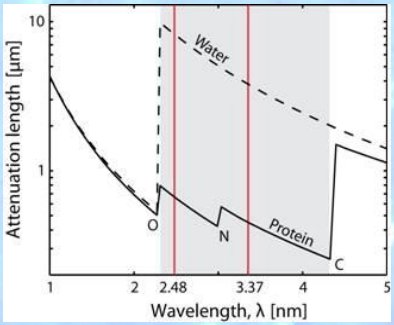
Higher energy (resolution) smaller pinholes, flux drop



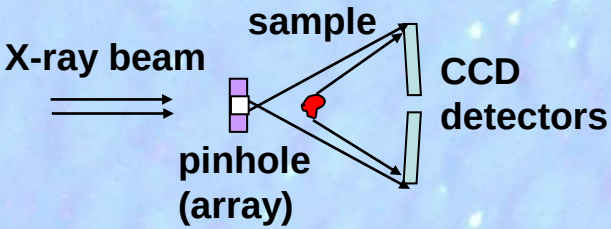
Beam focusing and splitting, coherent source re-created by the small output aperture (nm) very low flux trough the sample, small setup sizes, long exposures

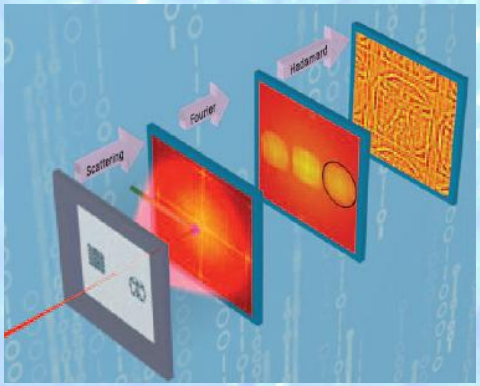
Solutions adopted in the low-energy range

Absorption XRH
water window (300-500 eV)

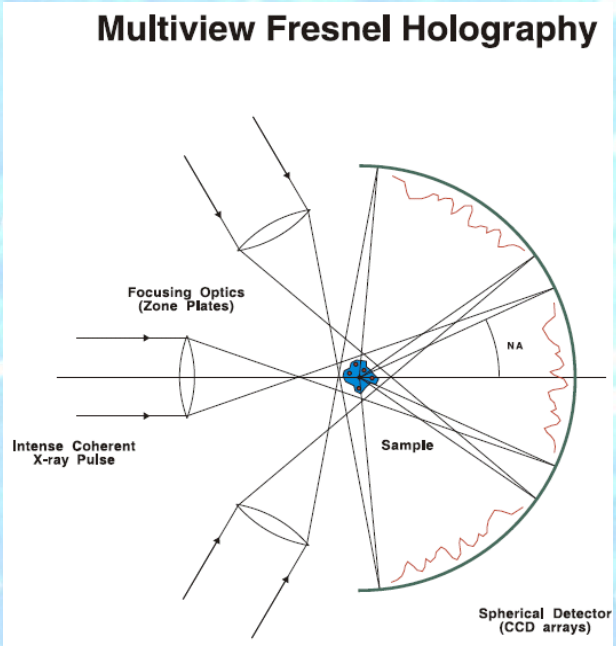


Contrast for structures based on C,N and heavier elements





Array of Hadamard pinholes
~50-75 nm resolution
Marchesini S. et. al.
Nature Photonics V 2 Sept 2008



-large angles -> near detector placement -> pitch and wavelength limited resolution

-pinhole limited flux

Absorption->shadow
Multiview needed to explore the whole 3D structure

Experimental difficulties in *X-ray digital holography*
(not encountered in the visible range)

- X-ray sources are complex; the degree of spatial coherence is limited and goes inversely with the flux and the energy (pinhole or focus size / distance), while good temporal coherence is achieved only with lasers

- high diffraction angles for absorption-based imaging, wide sensors should be used (detector pitch and size limit the resolution)

- sample size limited by the strong illumination needed

- shielding effect in the "water window" (further reducing the illumination)

- special optics (X-ray mirrors, Fresnel lenses), efficiency strongly drops with energy

- pinholes limiting the flux (size varying inversely with the energy)

- samples might be altered during exposure, by ionization and heating

- long exposures are resolution-limiting, due to system instability (vibrations, thermal)

Key elements for successful hi-res holography

- Higher energy -> pushing lower the diffraction limit

- Beam focusing on the sample (illumination)

- Magnification

- Beam splitting ("clean" reference)

- Small diffraction angles, allowing far detector placement and therefore, lower "grain". This is just apparently in contradiction with the first request (energy); switching from absorption to phase contrast reduces, for most biological samples (given the small internal variations in the refractive index), the characteristic angles by ~ 3 orders of magnitude

- Large detectors with small pitch (~25 um) placed at large distances

- Coherent, short time, high pulse intensity X-ray sources
  (to allow in-vivo imaging)

- Geometry / optics matching all the above constraints

Coherent X-ray sources

Conventional sources – monochromators – lenses - pinholes: extremely low flux, Doppler-broadening, sample internal dynamics and vibrations induce displacements larger than the investigated structure elements

Undulators on synchrotron beamlines: limited degree of coherence, low instantaneous intensity

Pulsed X-ray fluorescent sources, activated by high power lasers: high divergence, Doppler

Amplified Stimulated Emission (ASE) in plasma capillary columns or plasma electrons in microundulators (still under prototyping phase)

FELs - high brilliance, 10^{10}-10^{14} ph/pulse **(SASE)**
- coherent (high spatial, fair temporal coherence, improved by self-seeding)
- low divergence
- very short pulses (from 5 to 300 fs)

By eliminating the effect of vibrations and internal movement, inducing image smearing, the interference pattern becomes independent of sample degradation under incident radiation and therefore allows in vivo studies and pinning up ultra-fast processes

Current FEL-XFEL status

Operational FELs:

- SACLA at RIKEN, (up to 15 keV, ~5*10^{13} ph/pulse, 60 Hz)
- LCLS at SLAC (480 – 9500 eV, 10^{13}-10^{12} ph/pulse, 60-300 fs, 120 Hz)
- FLASH at DESY (300 eV, up to1keV harmonics, 10^{12} ph/pulse,10-100 fs)

  (LCLS and FLASH already realized XRH applications)
- FLASH II at DESY (up to 620 eV)
-European XFEL (DESY) 450 eV to 25 keV, 10^{14} ph/pulse, 27000 Hz, coherence time

  0.2-0.88 fs
- XFEL at PSI (3 lines, up to 12.4 keV, 5*10^{12} ph/pulse, 20 fs, 100 Hz)

Italian FELs:

- SPARC FEL at LNF Frascati (to date up to 30 eV)
- FERMI FEL2 at ELETTRA Trieste (124 eV, ~10^{11} ph/pulse)

FELs under design/commissioning: LUND FEL, PAL XFEL (12 keV), EuPRAXIA

Current project

Goal: to improve by one order of magnitude the current resolution limit of XRH, reaching the few nm range full 3D (no shadows) and to allow in-vivo ultrafast exposures.

What we cannot use (efficiently):

-Pinholes, masks: small surface, low energy range

-Pair of capillary waveguides: provide a low intensity beam

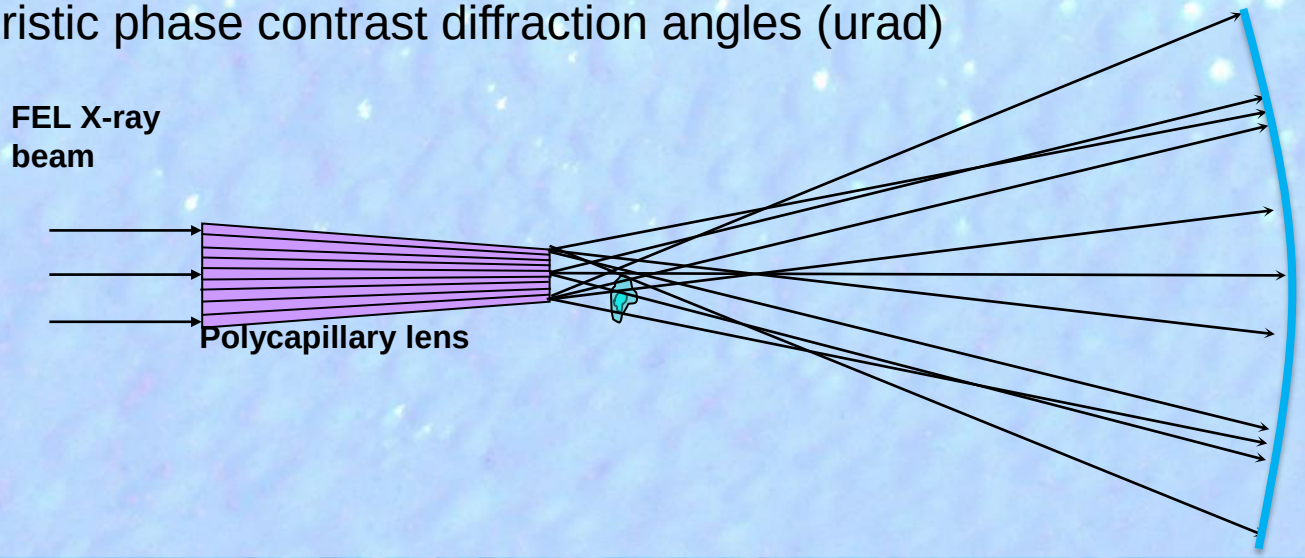
-Fresnel lens or mirrors used to focus are "perfect optics"; in phase contrast regime they cannot provide beam splitting (reference and object, crossing the sample) and overlap on the same detector area. Being the diffraction angles extremely small (μrad), the sample "shadow" will fall on a region unexposed to a reference.

Moreover, if focusing is used to obtain a coherent source (pinhole-like), the sample must be placed far away, so a low flux of photons will cross it.

Main ideas:

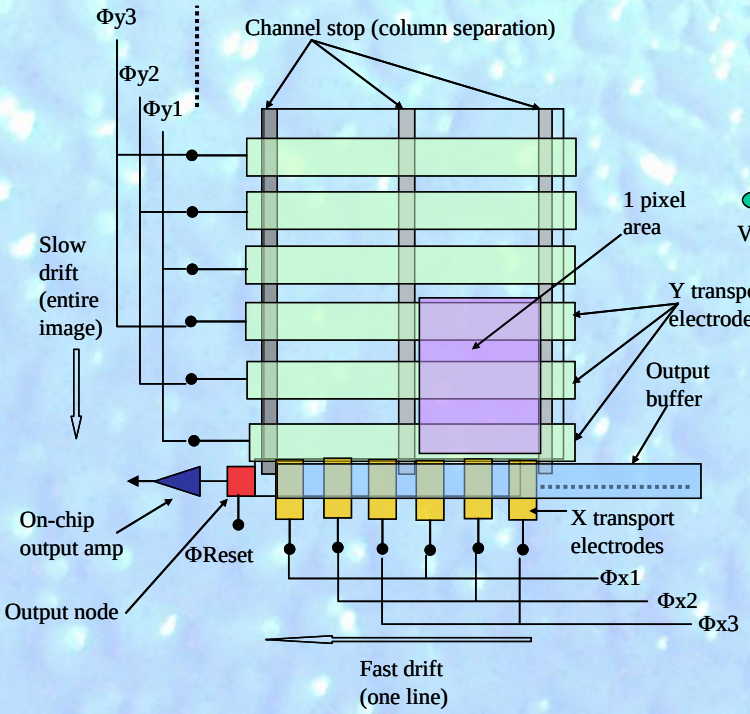
Capillary optics, XFEL beam, large array (Fresnel configuration) of deeply depleted, low pitch, cryogenic CCDs, placed far away from the sample, slow readout mode.

Polycapillary half-lenses will grant:
-coherent (waveguide) propagation
-intensity gain by focusing
-magnification
-beam splitting
-being imperfect optical elements, their divergence is not driven by the focal length but mainly by the single fiber output. This allows the overlap of the 2 "beams" on the same detection area
-good match between divergence (tens of mrad), detector and pixel size, distance and characteristic phase contrast diffraction angles (urad)

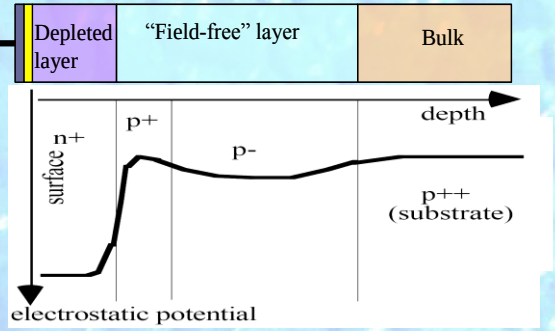


Deeply depleted X-Ray CCDs

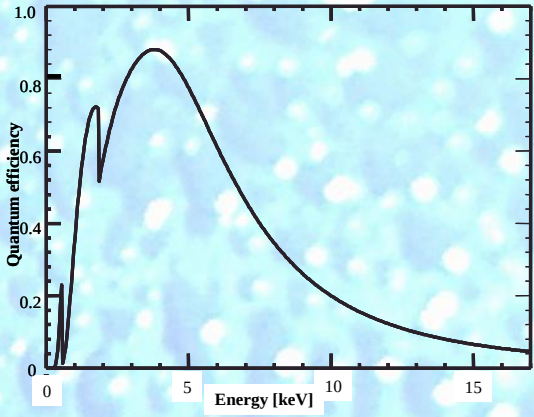
Electrode structure



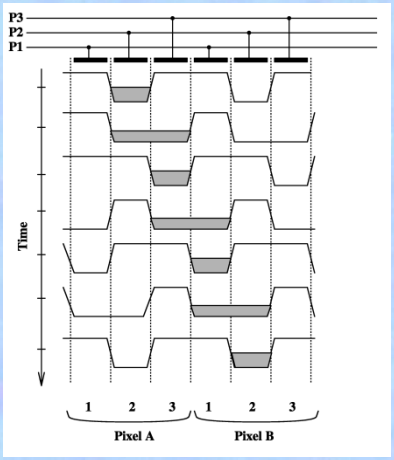
Electric field amplitude under a polarized electrode



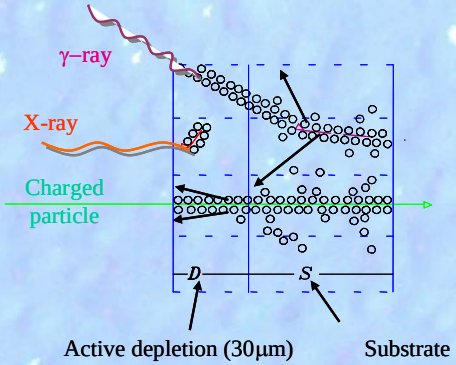
Quantum efficiency

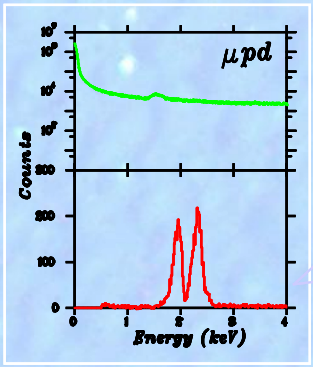


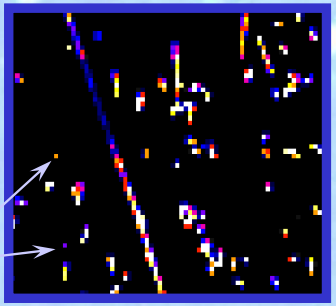
Charge transfer clocking



Background rejection by topological selection of single pixels







Assumptions

Working range: 3-4 keV, in order to push the resolution by 1 order of magnitude still maintaining a significant refractive index (above 15 keV becomes compatible to unity)

The deeply depleted CCDs have very good Q.E. in this range (80-90%).

Slow readout mode with cryogenics: allows reading images with few photons/pixel (1 to 10) without charge transport inefficiency "trails".

Some order of magnitude estimates for a 30 m baseline:

Fiber divergence 20 mrad -> 30m baseline -> ~20-30cm detector size (border beams partially lost) -> *~100 Mpixel*, for a pitch of ~ 25 um (minimum size to have good depletion and low escape) - good enough for starting doing holography

Low refractive index differences inside the sample -> few μrad diffractive angles -> 30 m -> 30 μm pixel for a good "Shannon" sampling

Phase contrast (transmission) eliminates the "shadow effect", allowing full 3D structure investigation with a single exposure

Frascati XRH project premises

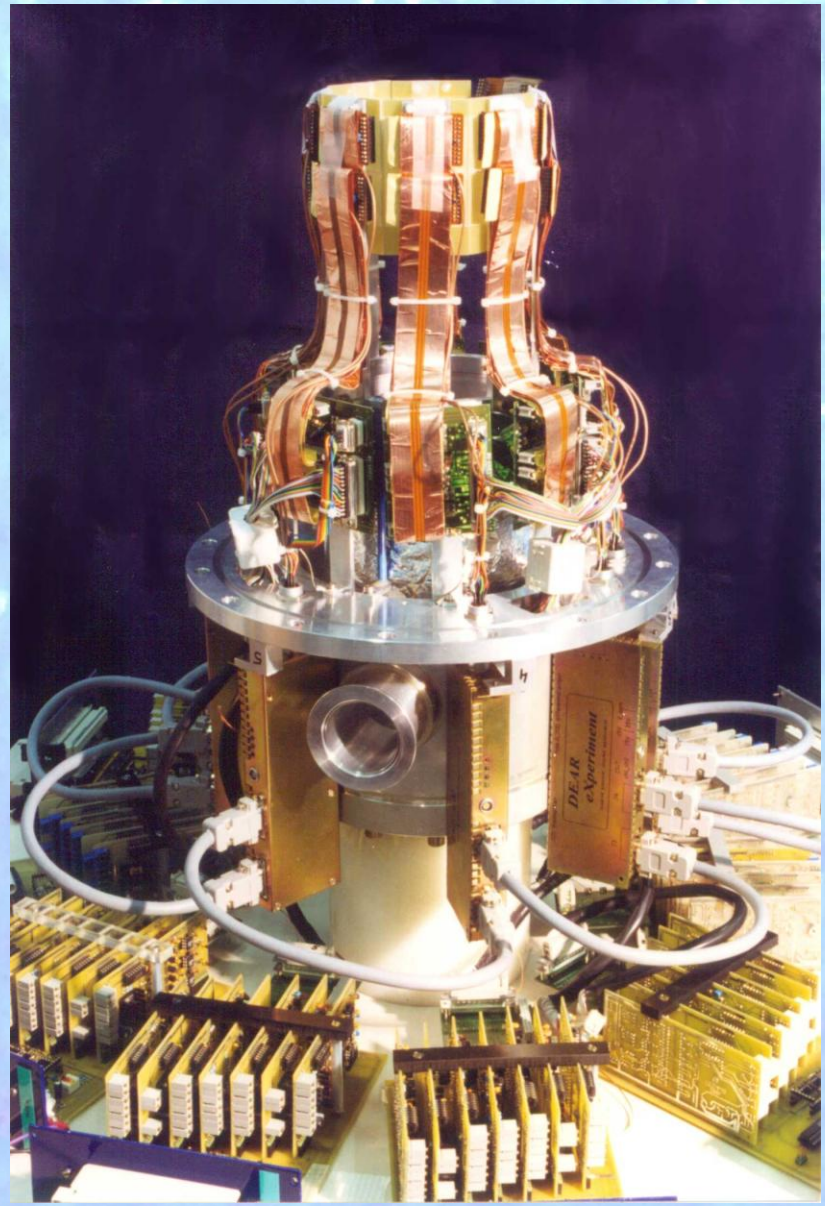
-Good knowledge in cryogenic silicon detector operation and readout systems development

-Direct collaboration with X-ray specialists working in sample analysis (Frascati synchrotron group), X-ray optics and nanotechnology development (X-Lab) and FEL/XFEL projects

-Availability of a large part of necessary instrumentation and detectors (deeply depleted CCDs, cryogenics, electronics and lab. equipment)

-A team fulfilling necessary competences required by the practical project implementation

DEAR/VIP apparatus



16 CCD-55-30 deeply depleted (Marconi)

pixel size of 22.5x22.5 μm

depletion depth of 30 μm

effective area of 7.3 cm^2

1430784 pixels each
(21.8 Mpixel, 116.8 cm^2)

Vacuum & cryogenics for -120C operation

Transport drivers

High precision spectroscopic amplifier

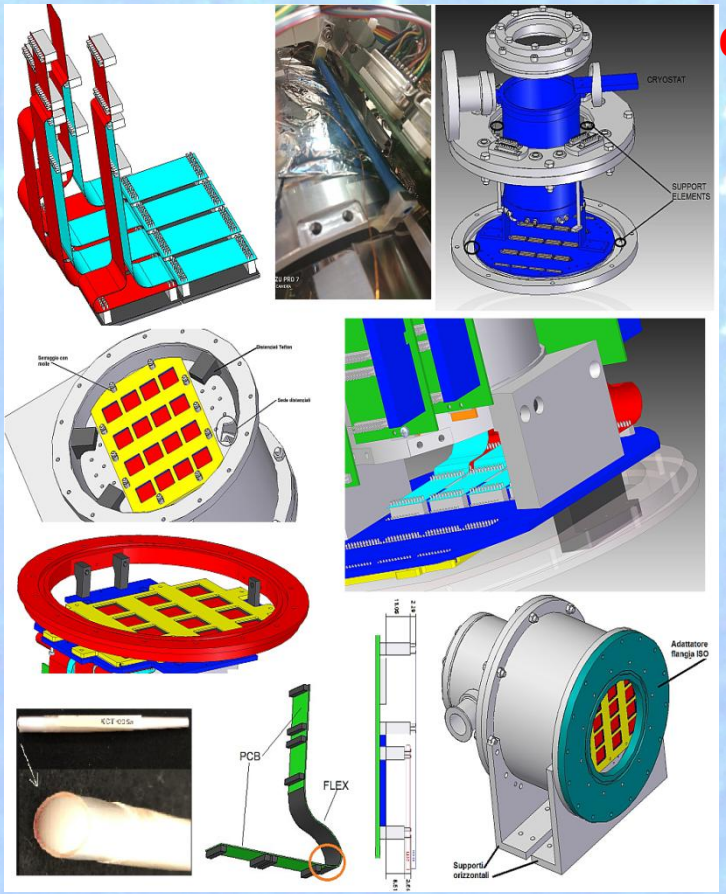
Software dual slope integrator

Fast DAQ (250-600 MB/s RT)

Noise reduction & charge transport correction algorithms implemented

Structure Probing by Holographic Imaging at Nanometer scale with X-ray lasers (SPHINX)

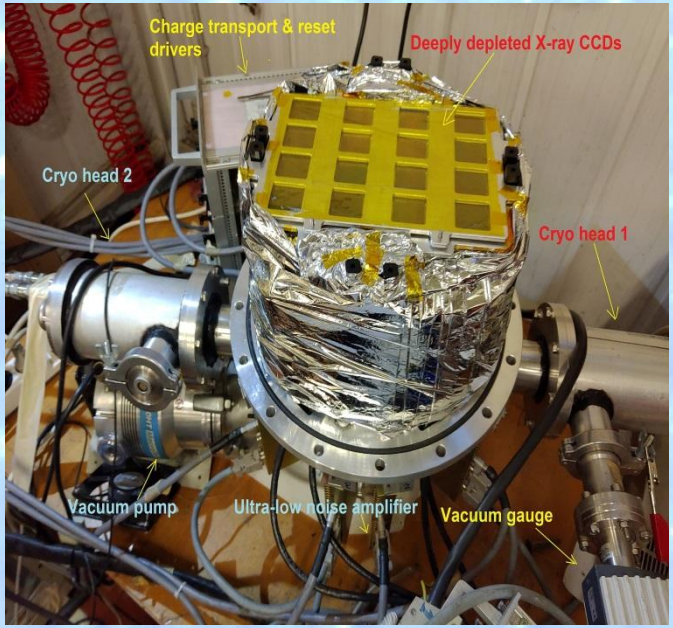
SPHINX aims producing an X-ray phase-contrast holography system for femtosecond imaging microscopic samples and their internal parts with nanometer resolution, using a combination of polycapillary lenses, large X-Ray CCD arrays and XFEL sources. The proposed configuration allows beam splitting, focusing, magnification and refractive diffraction in the keV range.

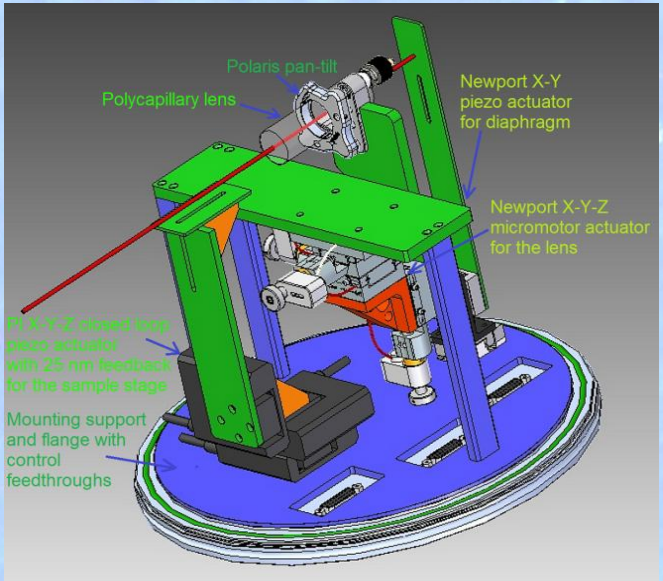


Current status:

1. Full design (mechanics, cryogenics and electronics) finalized; production in advanced phase.
2. First X-ray optics delivered, synchrotron tests in preparation.
3. DAQ and slow control software completed.
4. MC code in advanced phase; reconstruction program work initiated
5. Calibration system under development

Structure Probing by Holographic Imaging at Nanometer scale with X-ray lasers (SPHINX)





Prototype status:

1. Full detector assembly completed.

2 Vacuum and cryogenic testing completed.

3. Optics bench design completed, all components realized, ordered actuators arrived, second vacuum chamber and feedtrough flanges realized.

The bench parameters are:

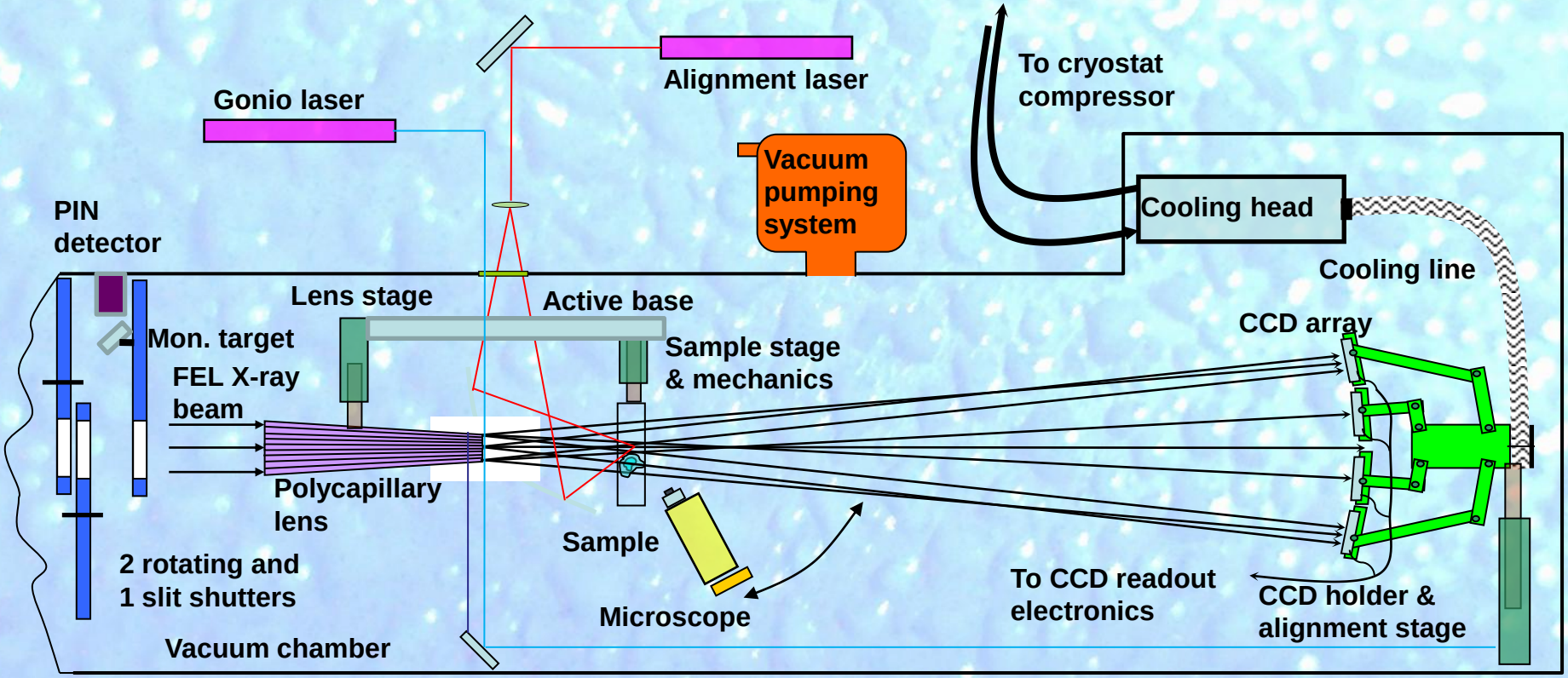
- **-10 degrees of freedom (8 translations, 2 rotations)**
- **-50 nanometer average precision**
- **-25 nm measurement feedback for the sample stage.**

Installation in advanced phase.

4. Measurement plan with DIAMOND synchrotron

5. Contact with European X-FEL established, more specific plans to follow the optics investigation.

Final XRH setup proposed layout



The final project aims realizing a soft X-ray holography apparatus for phase contrast imaging, based on a large area CCD array and new X-ray optics, to be used on the recently available XFELs. The XFEL beam will grant three of the critical parameters, namely the **coherence**, the **ultra-short exposure** and the **requested flux**. The large area deeply depleted CCD array will ensure the **full coverage of the useful solid angle**, while the **concentrated (over few um) X-ray source** will be created using **polycapillary optics**, on which many studies demonstrated a high degree of coherent propagation. The reference beam consists in the fraction of rays not crossing the sample, overlapping the last's one shadow over the whole detector area, **geometry uniquely allowed by capillary half-lenses**.

Closing notes

The resolution targeted by the proposed method represents a breakthrough in the field,

bringing the holography application in the **few nm range**, where **in-vivo** individual cell

elements (DNA, organelles, etc.), viruses, antibodies and proteins can be directly 3-D visualized.

The method might have applications in **nanorobotics**, too, where in-action visualization is still an issue.

Moreover, the ultra-short exposures (tens of fs) allow reconstruction of sample

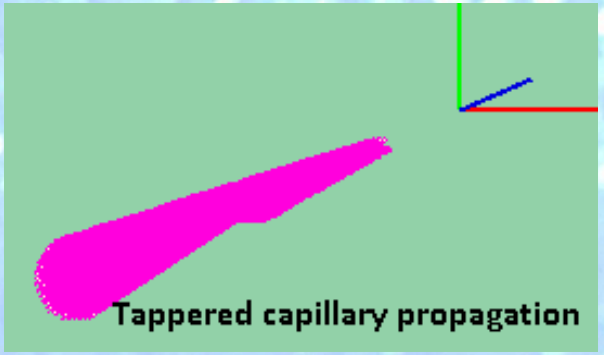
configuration during **fast molecular interactions**, yet unexplored by imaging techniques.

Comments

A common question about the coherent source: after the propagation inside capillaries, the photon paths will be different one from the other, so transforming the initial "flat" wavefront in a very complex one. Will this worsen the reconstruction? The answer from ptychography results is: no, the complex wavefront, if properly known (scanned), will offer a better reconstruction reference than the lab system, unstable at nm level. Some bibliography demonstrating the idea is cited below (much wider is available):

Coherent propagation in capillaries investigated in [1, 2, 3, 4]
Ptychographic phase mapping and reconstruction methods validated in [5, 6]
Coherent holographic reconstruction up to 12 KeV with single, tapered and bent glass capillary waveguides was treated in [2].

1. S.B. Dabagov, H. Uberall, NIM B 266 (2008)
2. C.Fuhse, PhD Thesis Gottingen Univ. (2006)
3. A. M. Zysk et. al, Optics Express V. 20, No. 4, 3975
4. S.B. Dabagov et. al, Appl. Optics,V39,N19 (2000)
5. **Marco S. et. al.** ***Scientific Reports 3 : 1927 (2013)***
6. P. Thibault et. al., "High-resolution scanning X-ray diffraction microscopy," Science 321, 379–382 (2008)



In order to estimate possible outcome, a Monte Carlo development is ongoing:
-to properly reconstruct the phase map at the lens output, 740 billion photons are propagated trough each fiber with a path computed in double precision
-a parallel algorithm (OMP based), able to efficiently distribute the threads on as many cores as available was developed
-the run-time is long, with the available means; however, a first result for a reduced set of capillaries is expected to be available soon